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FORM PTO-1390 REV. 5-93 US DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE **TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371**		ATTORNEYS DOCKET NUMBER **P01,0008** U.S. APPLICATION NO. (if known, see 37 CFR 1.5) 09/762508
INTERNATIONAL APPLICATION NO. **PCT/DE99/02590**	INTERNATIONAL FILING DATE **18 AUGUST 1999**	PRIORITY DATE CLAIMED **20 AUGUST 1998**
TITLE OF INVENTION **THERMAL WAVE MEASURING METHOD**		
APPLICANT(S) FOR DO/EO/US **JOACHIM BAUMANN ET AL.**		

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☒ This express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay.
4. ☒ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. ☒ A copy of International Application as filed (35 U.S.C. 371(c)(2)) - drawings attached.
   a. ☒ is transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☐ has been transmitted by the International Bureau.
   c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US)
6. ☒ A translation of the International Application into English (35 U.S.C. 371(c)(2) - drawings attached.
7. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. §371(c)(3))
   a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☐ have been transmitted by the International Bureau.
   c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
   d. ☒ have not been made and will not be made.
8. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. ☐ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11. to 16. below concern other document(s) or information included:

11. ☐ An Information Disclosure Statement under 37 C.F.R. 1.97 and 1.98; **(PTO 1449, Prior Art, Search Report, 10 References)**.
12. ☒ An assignment document for recording. A separate cover sheet in compliance with 37 C.F.R. 3.28 and 3.31 is included. **(SEE ATTACHED ENVELOPE)**
13. ☒ Amendment "A" Prior to Action and Appendix "A".
    ☐ A SECOND or SUBSEQUENT preliminary amendment.
14. ☒ A substitute specification and substitute specification mark-up.
15. ☒ A change of address letter attached to the Declaration.
16. ☒ Other items or information:
    a. ☒ Appointment of Associate Power of Attorney
    b. ☒ EXPRESS MAIL #EL655300814US dated February 7, 2001.

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U.S. APPLICATION NO. (if known, see 37 C.F.R. 1.5) 09/762508	INTERNATIONAL APPLICATION NO. PCT/DE99/02590	ATTORNEY'S DOCKET NUMBER P01,0008

17. ☒ The following fees are submitted:

				CALCULATIONS	PTO USE ONLY
BASIC NATIONAL FEE (37 C.F.R. 1.492(a)(1)-(5): Search Report has been prepared by the EPO or JPO . . . . $860.00 International preliminary examination fee paid to USPTO (37 C.F.R. 1.482) . . $690.00 No international preliminary examination fee paid to USPTO (37 C.F.R. 1.482) but international search fee paid to USPTO (37 C.F.R. 1.445(a)(2) . . . . $710.00 Neither international preliminary examination fee (37 C.F.R. 1.482) nor international search fee (37 C.F.R. 1.445(a)(2) paid to USPTO . . . . $1000.00 International preliminary examination fee paid to USPTO (37 C.F.R. 1.482) and all claims satisfied provisions of PCT Article 33(2)-(4) . . . . $ 100.00					
ENTER APPROPRIATE BASIC FEE AMOUNT =				$ 860.00	
Surcharge of $130.00 for furnishing the oath or declaration later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 C.F.R. 1.492(e)).				$	
Claims	Number Filed	Number Extra	Rate		
Total Claims	10 - 20 =	0	X $ 18.00	$	
Independent Claims	01 - 3 =	0	X $ 80.00	$	
Multiple Dependent Claims			$270.00 +	$	
TOTAL OF ABOVE CALCULATIONS =				$ 860.00	
Reduction by ½ for filing by small entity, if applicable. Verified Small Entity statement must also be filed. (Note 37 C.F.R. 1.9, 1.27, 1.28)				$	
SUBTOTAL =				$ 860.00	
Processing fee of $130.00 for furnishing the English translation later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492(f)). +				$	
TOTAL NATIONAL FEE =				$ 860.00	
Fee for recording the enclosed assignment (37 C.F.R. 1.21(h). The assignment must be accompanied by an appropriate cover sheet (37 C.F.R. 3.28, 3.31). $40.00 per property +					
TOTAL FEES ENCLOSED =				$ 860.00	
				Amount to be refunded	$
				charged	$

a. ☒ A check in the amount of $ 860.00 to cover the above fees is enclosed.

b. ☐ Please charge my Deposit Account No. ____________ in the amount of $ ________ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 50-1519. **A duplicate copy of this sheet is enclosed.**

NOTE: Where an appropriate time limit under 37 C.F.R. 1.494 or 1.495 has not been met, a petition to revive (37 C.F.R. 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

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BOX PCT
IN THE UNITED STATES DESIGNATED/ELECTED OFFICE
OF THE UNITED STATES PATENT AND TRADEMARK OFFICE
UNDER THE PATENT COOPERATION TREATY--CHAPTER II

PRELIMINARY AMENDMENT A
PRIOR TO ACTION

APPLICANT(S):	JOACHIM BAUMANN ET AL
ATTORNEY DOCKET NO.:	P01,0008
INTERNATIONAL APPLICATION NO:	PCT/DE99/02590
INTERNATIONAL FILING DATE:	18 AUGUST 1999

INVENTION: THERMAL WAVE MEASURING METHOD

Assistant Commissioner for Patents,
Washington D.C. 20231

Sir:

Applicants herewith amend the above-referenced PCT application, and request entry of the Amendment prior to examination on the United States Examination Phase.

IN THE CLAIMS:

On page 7:

replace line 1 with --WHAT IS CLAIMED IS:--;

Please replace original claims 1-8 with the following rewritten claims 1-8, referring to the mark-ups in Appendix A.

1. (Amended) A thermal wave measuring method for contact-free measurement of geometrical or thermal features of a layer structure, comprising the steps of:

simultaneously driving a modulatable heat source with at least two predetermined discrete different frequencies in an amplituded-modulated manner,

thereby periodically heating said layer structure;

receiving infrared radiation emitted by said layer structure that is correspondingly modulated in intensity; and

evaluating said received infrared radiation as a function of a drive frequency on the basis of amplitude or phase by simultaneously interpreting corresponding drive frequencies.

2. (Amended) The method according to claim 1, wherein said heat source is a laser, a laser diode, or a light-emitting diode.

3. (Amended) The method according to claim 1, further comprising the step of:

adapting discrete frequency parts of said drive frequencies to a measurement function.

4. (Amended) The method according to claim 1, further comprising the step of:

detecting predetermined frequencies with a lock-in evaluation.

5. (Amended) The method according to claim 1, further comprising the step of:

evaluating individual frequencies using a Fast Fourier Transform.

6. (Amended) The method according to claim 4:

further comprising the step of providing an additional evaluation based on a regression analysis or a neural network.

7. (Amended) The method according to claim 1, further comprising the step of:

calibrating said method to a specific layer structure utilizing mathematically specific, theoretical values as well as utilizing experimentally supported data.

8. (Amended) The method according to claim 1, further comprising the step of:

determining geometrical features given known thermal features of the layer structure.

Please add the following new claims 9-10.

9. (New) The method according to claim 5:

further comprising the step of providing an additional evaluation based on a regression analysis or a neural network.

10. (New) The method according to claim1, further comprising the step of:

determining thermal features given known geometrical features of the layer structure.

REMARKS

The present Amendment revises the specification and claims to conform to United States patent practice, before examination of the present PCT application in the United States National Examination Phase. Pursuant to 37 CFR 1.125 (b), applicants have concurrently submitted a substitute specification, excluding the claims, and provided a marked-up copy. All of the changes are editorial and applicant believes no new matter is added thereby. The amendment, addition, and/or cancellation of claims is not intended to be a surrender of any of the subject matter of those claims.

Early examination on the merits is respectfully requested.

Submitted by,

(Reg. No. 45,877)

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Appendix A
Mark Ups for Claim Amendments

This redlined draft, generated by CompareRite (TM) - The Instant Redliner, shows the differences between -
original document : Q:\DOCUMENTS\YEAR 2001\P010008-BAUMANN-THERMAL WAVE MEASURING\ORIGINAL CLAIMS.DOC
and revised document: Q:\DOCUMENTS\YEAR 2001\P010008-BAUMANN-THERMAL WAVE MEASURING\AMENDED CLAIMS.DOC

CompareRite found 40 change(s) in the text

Deletions appear as Overstrike text surrounded by []
Additions appear as Bold-Underline text

1. [~~Thermal~~]**(Amended) A thermal** wave measuring method for contact-free measurement of geometrical [~~and/or~~] **or** thermal features of a layer structure, [~~whereby~~] **comprising the steps of:**

simultaneously driving a modulatable heat source [~~is driven with~~]**with at least two predetermined discrete** different frequencies [~~and the~~] **in an amplituded-modulated manner, thereby periodically heating said** layer structure [~~is periodically heated,~~]**;**

receiving infrared radiation emitted by [~~the~~] **said** layer structure [~~and~~] **that is** correspondingly modulated in intensity [~~is~~]**; and**

evaluating said received [~~and is respectively evaluated as~~]**infrared radiation as a** function of a drive frequency on the basis of amplitude [~~and/or phase, whereby the heat source is simultaneously amplitude-modulated with at least two, predetermined, discrete frequencies, and the infrared radiation emitted by the layer structure is~~] **or phase by** simultaneously [~~interpreted~~] **interpreting** corresponding [~~to the~~] drive frequencies.

2. [~~Method~~]**(Amended) The method** according to claim 1, wherein [~~a laser or, respectively~~] **said heat source is a laser**, a laser diode**,** or a light-emitting diode[~~(LED) is employed as heat source.~~]**.**

~~[3. Method]~~ **3. (Amended) The method** according to ~~[one of the preceding claims, wherein the]~~ **claim 1, further comprising the step of:**

adapting discrete frequency parts of ~~[the]~~ **said** drive frequencies ~~[are adapted]~~ to a measurement ~~[problem.]~~ **function.**

~~[4. Method]~~ **4. (Amended) The method** according to claim 1 ~~[or 2, wherein the]~~**, further comprising the step of:**

detecting predetermined frequencies ~~[are detected]~~ with a lock-in evaluation.

5. ~~[Method]~~**(Amended) The method** according to claim 1, ~~[2 or 3, wherein a fast]~~ **further comprising the step of:**

evaluating individual frequencies using a Fast Fourier ~~[transformation (FFT) is provided for the evaluation of the individual frequencies.]~~ **Transform.**

~~[6. Method]~~ **6. (Amended) The method** according to claim 4 ~~[or 5, wherein a farther-reaching]~~**:**

further comprising the step of providing an additional evaluation ~~[occurs]~~ **based** on ~~[the basis of]~~ a regression analysis or ~~[with]~~ a neural network.

7. ~~[Method]~~**(Amended) The method** according to ~~[one of the preceding claims, wherein the method is calibrated]~~ **claim 1, further comprising the step of:**

calibrating said method to a specific layer structure ~~[with calibration both my means of]~~ **utilizing** mathematically specific, theoretical values as well as ~~[by]~~ **utilizing** experimentally supported data.

8. ~~[Method]~~**(Amended) The method** according to ~~[one of the preceding claims for]~~ **claim 1, further comprising the step of:**

determining geometrical features given known thermal ~~[features or thermal features given known geometrical]~~ features of the layer structure.

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SPECIFICATION

TITLE

THERMAL WAVE MEASURING METHOD

BACKGROUND OF THE INVENTION

Field of the Invention

The invention is directed to a fast, contact-free, geometrical as well as thermal characterization of a planar multi-layer structure.

Description of the Related Art

Measurements with respect to such characterizations are demanded, for example, in automotive multi-coat lacquering. The category of thermal wave measuring methods are known, for example, under the designations heat sources, photothermal and photoacoustic methods or lock-in thermography.

Methods that, for example, go by the name "photothermal measuring methods, thermal wave measuring methods or lock-in thermography" are known in the Prior Art. In these methods, a material to be tested and having a superficial layer structure is heated periodically and in regions with a heat source. The heating must be capable of being modulated, so that an amplitude modulation is present. The modulation frequencies of the heating can thus be sequentially tuned, and the photothermal signal that derives from a specimen is measured as a function of the frequency based on amplitude and, in particular, its phase. The evaluation in terms of two or more unknowns (for example, layer thicknesses) can generally not be implemented in closed analytical form since an "inverse problem" is present here, i.e., the solving of the equation system for an unknown is not possible without further effort.

Disadvantages of the methods belonging to the Prior Art are that the sequential tuning of the modulation frequency of the modulatable heat source lasts a long time.

SUMMARY OF THE INVENTION

The invention is based on the object of providing a thermal wave measuring method that achieves a significant speed-up of a corresponding measurement and evaluation. A critical goal is to use a fast thermal wave measuring method for monitoring layering structures in ongoing production.

This object is achieved by a thermal wave measuring method for contact-free measurement of geometrical or thermal features of a layer structure, comprising the steps of simultaneously driving a modulatable heat source with at least two predetermined discrete different frequencies in an amplitude-modulated manner, thereby periodically heating the layer structure; receiving infrared radiation emitted by the layer structure that is correspondingly modulated in intensity; and evaluating the received infrared radiation as a function of a drive frequency on the basis of amplitude or phase by simultaneously interpreting corresponding drive frequencies.

The invention is based on the notion that the heat source employed for the regional heating of a layer structure can be simultaneously driven with a plurality of different frequencies and the infrared radiation corresponding to the drive frequencies can be simultaneously evaluated. Thus, specific supporting points can be determined from a characteristic for the sequential tuning of the heat source over the frequency, a specific plurality of different, discrete frequencies deriving from this. These are simultaneously employed for the drive of the heat source, so that the actual tuning of the heat source over the frequency is no longer implemented, resulting in a significant time-savings.

Further inventive developments are as follows. The heat source for the inventive method may be a laser, a laser diode, or a light-emitting diode. The discrete frequency parts of the drive frequencies may be adapted to a measurement function. The predetermined frequencies may be detected with a lock-in evaluation, and individual frequencies may be evaluated using a Fast Fourier Transform. An additional evaluation may be provided using a regression analysis or a neural network. The method may be calibrated to a specific layer structure utilizing mathematically specific, theoretical values as well as utilizing experimentally supported data. Geometrical features may be determined given known thermal

features of the layer structure, or visa versa. These developments are described in greater detail below.

A light-emitting diode (LED) or a laser diode can be advantageously utilized as heat source since they can be electrically amplitude-modulated. Fundamentally, all heat sources can be utilized that offer the possibility of an electrical modulation to implement a multi-frequency excitation.

When a specific layer sequence is present at the surface of a specimen, then a subject-related setting of the drive frequencies can be advantageously undertaken at the heat source. The relationship applies that an increasing penetration depth into the layer structure accompanies dropping modulation frequency at the heat source. The selection of the drive frequencies can be advantageously set in conformity with a known layer structure.

The target quantities, for example individual layer thicknesses, can be numerically determined with the approach of a regression analysis with non-linear formulation functions or, respectively, with a trainable neural network. Experimental or theoretical/analytical supporting values can thereby be employed as calibration values.

BRIEF DESCRIPTION OF THE DRAWINGS

Further exemplary embodiments are described below on the basis of the following Figures.

Figure 1 is a schematic block diagram showing a test setup for the implementation of a method according to the invention;

Figure 2 is a graph showing the phase shift of reflected heat waves dependent on the drive frequency of a heat source;

Figure 3 is a graph showing a reference and detector signal given a modulation of 10 Hz for two frequency generators (choppers);

Figure 4 is a graph showing a reference and phase signal given a modulation of 10 Hz for both choppers 1, 2;

Figure 5 is a graph showing a reference and detector signal given a modulation of 40 and 20 Hz; and

Figure 6 is a graph showing a reference and phase signal given a modulation of 40 and 20 Hz.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The measuring time for a measurement and evaluation using a thermal wave measuring method is drastically shortened as a result of the simultaneous multi-frequency excitation and simultaneous parallel interpretation in view of the various frequencies or the different, reflected, corresponding infrared radiation. As a result of a suitable selection of the individual frequency parts, the frequency range of measurement in which the heat source is driven can be exactly matched to the measurement problem. The simultaneous intensity modulation with two or more discrete frequencies onto an electrically modulatable heat source enables the parallel interpretation in a corresponding plurality of lock-in amplifiers. Alternately, the signal interpretation can also ensue with an FFT or similar digital evaluation method such as correlation or fitting to a sine function using a digital oscilloscope.

A hot light source such as a laser diode or an LED is usually employed as heat source. Either regression analysis or a neural network can be utilized for evaluation following a corresponding plurality of lock-in amplifiers or a fast Fourier transformation.

The critical feature of the invention is the simultaneity with which a heat source is driven with different frequencies. When, for example, three frequencies have been selected, then their sum supplies an analog signal with which the heat source is modulated. A corresponding evaluation is carried out simultaneously for each frequency at the evaluation side.

In a test setup corresponding to Figure 1, a standard specimen 7 that is composed of a TiN layer on a glass lamina is measured. A heat ray output by a laser 3 heats the specimen by regions. The heat ray is divided after exiting the laser, and each of the two rays is supplied to a mechanical chopper 1, 2. When passing through the choppers 1, 2, the two rays are modulated with different modulation frequencies f1, f2 and are subsequently focused in common and directed onto the specimen 7. As a result, it is also possible with a mechanical modulation to

simultaneously excite the specimen with two modulation frequencies. An electronic processing of the various frequencies is advantageous. After the detector signal 8 has been forwarded to two different lock-in amplifiers 10, 20, two phases 11, 21 that can be displayed on a storage oscilloscope 13 are correspondingly obtained as result. The respective reference input 12, 21 of the lock-in amplifiers 10, 20 is occupied with the modulation frequency of the choppers 1, 2. In order to adapt the two beam paths to one another, a phase-frequency curve is first registered, i.e., the frequency of both choppers 1, 2 is simultaneously tuned. The result is shown in Figure 2 illustrates that the frequency shift arises at approximately -45° with higher frequencies of more than approximately 20 Hz. This is true both for chopper 1 and for chopper 2.

Figure 3 shows the results when both choppers 1, 2 are permanently set to 10 Hz and the detector signal 8 is measured. A frame with three values is respectively shown in the illustrations of Figures 3-6 to the left next to each signal curve. The first two of these values denote the scaling on the axes of the storage oscilloscope. The first value states how many milliseconds between two markings in a box on the abscissa, on which the time is denoted. The second value states how many volts on the ordinate, on which the voltage is denoted, the distance between two markings or in a box amounts to. The third value represents the actual result, namely a specific voltage that, counted in volts or millivolts, can be converted, for example, for an amplitude signal or a phase signal.

Measured values for reference, phase and detector signal given a 10 Hz modulation of both choppers 1, 2 are respectively shown on Figures 3 and 4. The same presentations as in Figures 3 and 4 are employed in Figures 5 and 6, in which, however, the modulation of the first chopper 1 amounts to 40 Hz and that of the second chopper 2 amounts to 20 Hz.

The basis of the illustrated measured values and results according to Figure 4 reflects that both choppers are permanently set to 10 Hz, and that the detector signal 8 is measured. The uppermost curve at the right represents the curve of the pulse sequence at the chopper 1. A complete oscillation requires the length of two boxes or twice 50 ms, so that a frequency of 10 Hz is present. The same is true of

the middle curve, which is present at the second chopper 2. The lowest curve represents the detector signal 8, which is an analog signal at first. In all three instances, the amplitude of the signal is respectively entered as the third value in the juxtaposed frame; these, however, are selectable trial parameters.

Figure 2 shows both the reference as well as the phase given a modulation of 10 Hz for both choppers 1, 2. The pulse frequency is identical to the frequency in Figure 3. The phase position of the choppers 1, 2 is nearly identical to -584 mV and -591 mV which, when converted, approximately corresponds to a phase shift of 60°. Thus, 10 mV stands for a 1° phase shift--in other words, the infrared wave or heat wave reflected back from the specimen 7 has a phase position that lags behind the phase of the laser signal by 60°.

Figure 5 and 6 show signals corresponding to Figures 3 and 4. In this case, however, the first and second chopper 1, 2 are modulated on different frequencies. The first chopper 1 respectively comprises a pulse frequency of 40 Hz, and the second chopper 2 comprises a pulse frequency of 20 Hz. The detector signal 8 is again a result signal superimposed of a plurality of signals that is converted via the signal processing applied in the method. Corresponding to the second and fourth signal in Figure 6, the phase position for the two drive frequencies is also approximately the same for the case illustrated in Figures 5 and 6.

The measurements can thus document that it is possible to also correctly obtain the phase when the specimen is simultaneously modulated with two different frequencies instead of tuning the modulation frequency (chirp) as previously.

The measurement with the described mechanical choppers represents only one embodiment in which the modulation of laser diodes or of LEDs with a plurality of frequencies simultaneously is planned. Over and above this, the planar illumination of the specimen 8 can be optimized with appropriate devices, as can the image registration with a camera arrangement. The basis continues to be formed by the principle that the measuring time is shortened by simultaneous multi-frequency excitation and by simultaneous parallel evaluation of the different frequencies.

A requirement to simultaneously determine the geometrical and thermal parameters of a multi-layer structure may not be possible with traditional calculating

methods. An analytical formula for the phase dependent on the thermal and geometrical parameters as well as on the modulation frequency can be specified. When, however, this is to be solved for the quantities characterizing the multi-layer structure, then this is not possible analytically. This means that there is an "inverse problem". The interpretation can then ensue on the basis of numerical methods such as regression analysis or with a neural network, which represents an automation of the determination of the material parameters and involves a higher precision and a time-savings. Moreover, the possibility is opened up of theoretically describing arbitrary layer structures to be photothermally measured and of determining their thermal and geometrical properties.

The above-described method is illustrative of the principles of the present invention. Numerous modifications and adaptations will be readily apparent to those skilled in this art without departing from the spirit and scope of the present invention.

ABSTRACT

The simultaneous multi-frequency excitation with two or more discrete frequencies of an electrically modulatable hot light source enables a parallel evaluation corresponding to the different drive frequencies. As a result, the measuring time in the measurement of multi-layer systems is significantly shortened. As a result of a suitable selection of the discrete frequency parts of the drive frequencies, these can be adapted to the measurement problem.

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THERMAL WAVE MEASURING METHOD

The invention is directed to a fast, contact-free, geometrical as well as thermal characterization of a planar multi-layer structure. Measurements with respect thereto are in demand, for example, in automotive multi-coat lacquering. The category of thermal wave measuring methods are known, for example, under the designations heat sources, photothermal and photoacoustic methods or lock-in thermography.

Methods that, for example, pass by the name "photothermal measuring methods, thermal wave measuring methods or lock-in thermography" belong to the Prior Art. Therein, a material to be tested and having a superficial layer structure is heated periodically and in regions with a heat source. The heating must be capable of being modulated, so that an amplitude modulation is present. The modulation frequencies of the heating can thus be sequentially tuned, and the photothermal signal that derives from a specimen is measured as a function of the frequency based on amplitude and, in particular, its phase. The evaluation in terms of two or more unknowns (for example, layer thicknesses) can thereby generally not be implemented in closed analytical form since an "inverse problem" is present here. This is equivalent to saying that the solving of the equation system for an unknown is not possible without further ado.

Disadvantages of the methods belonging to the Prior Art are comprised, for example, therein that the sequential tuning of the modulation frequency of the modulatable heat source lasts a long time.

The invention is based on the object of offering a thermal wave measuring method with which a significant speed-up of a corresponding measurement and evaluation can be achieved. A critical goal is comprised in the use of a fast thermal wave measuring method for monitoring layering structures in ongoing production.

This object is achieved by the feature combination of claim 1.

The invention is based on the perception that the heat source employed for the regional heating of a layer structure can be simultaneously driven with a plurality of different frequencies and the infrared radiation corresponding to the drive

frequencies can be simultaneously evaluated. Thus, specific supporting points can be determined from a characteristic for the sequential tuning of the heat source over the frequency, a specific plurality of different, discrete frequencies deriving therefrom. These are simultaneously employed for the drive of the heat source, so that the actual tuning of the heat source over the frequency is no longer implemented, a significant time-savings deriving therefrom.

Further developments can be derived from the subclaims.

In particular, a light-emitting diode (LED) or a laser diode can be advantageously utilized as heat source since they can be electrically amplitude-modulated. Fundamentally, all heat sources can be utilized that offer the possibility of an electrical modulation such that a multi-frequency excitation can be implemented.

When a specific layer sequence is present at the surface of a specimen, then a subject-related setting of the drive frequencies can be advantageously undertaken at the heat source. The relationship applies that an increasing penetration depth into the layer structure accompanies dropping modulation frequency at the heat source. The selection of the drive frequencies can be advantageously set in conformity with a known layer structure.

The target quantities, for example individual layer thicknesses, can be numerically determined with the approach of a regression analysis with non-linear formulation functions or, respectively, with a trainable neural network. Experimental or theoretical/analytical supporting values can thereby be employed as calibration values.

Further advantageous developments can be derived from the subclaims.

Further exemplary embodiments are described below on the basis of schematic Figures.

Figure 1 shows a test setup for the implementation of a method according to the invention;

Figure 2 shows the phase shift of reflected heat waves dependent on the drive frequency of a heat source;

Figure 3 shows reference and detector signal given a modulation of 10 Hz for two frequency generators (choppers);

Figure 4 shows reference and phase signal given a modulation of 10 Hz for both choppers 1, 2;

Figure 5 shows reference and detector signal given a modulation of 40 and 20 Hz;

Figure 6 shows reference and phase signal given a modulation of 40 and 20 Hz.

The measuring time is drastically shortened as a result of the simultaneous multi-frequency excitation and simultaneous parallel interpretation in view of the various frequencies or, respectively, the different, reflected, corresponding infrared radiation. As a result of a suitable selection of the individual frequency parts, the frequency range of measurement in which the heat source is driven can thereby be exactly matched to the measurement problem. The simultaneous intensity modulation with two or more discrete frequencies onto an electrically modulatable heat source enables the parallel interpretation in a corresponding plurality of lock-in amplifiers. Instead, the signal interpretation can also ensue with a FFT or similar digital evaluation method such as correlation or fitting to a sine function upon utilization of a digital oscilloscope.

A hot light source such as, for example, a laser diode or an LED is usually employed as heat source. Either regression analysis or a neural network can be utilized for evaluation following a corresponding plurality of lock-in amplifiers or a fast Fourier transformation.

The critical feature of the invention is comprised in the simultaneity with which a heat source is driven with different frequencies. When, for example, three frequencies have been selected, then their sum supplies an analog signal with which the heat source is modulated. Corresponding evaluation is carried out for each frequency at the evaluation side. This occurs simultaneously.

In a test setup corresponding to Figure 1, a standard specimen that is composed of a TiN layer on a glass lamina is measured. A heat ray output by a laser 3 thereby heats the specimen by regions. The heat ray is divided after exiting the laser, whereby each of the two rays is supplied to a mechanical chopper 1, 2. When passing through the choppers 1, 2, the two rays are modulated with different

modulation frequencies f1, f2 and are subsequently focused in common and directed onto the specimen 7. As a result thereof, it is also possible with mechanical modulation to simultaneously excite the specimen with two modulation frequencies. An electronic processing of the various frequencies is advantageous. After the detector signal 8 has been forwarded to two different lock-in amplifiers 10, 20, two phases 11, 21 that can be displayed on a storage oscilloscope 13 are correspondingly obtained as result. The respective reference input 12, 21 of the lock-in amplifiers 10, 20 is occupied with the modulation frequency of the choppers 1 or, respectively, 2. In order to adapt the two beam paths to one another, a phase-frequency curve is first registered, i.e. the frequency of both choppers 1, 2 is simultaneously tuned. The result is shown in Figure 2. It can be seen in Figure 2 that the frequency shift arises at approximately -45° with higher frequencies of more than approximately 20 Hz. This is true both for chopper 1 and for chopper 2.

Figure 3 shows the results when both choppers 1, 2 are permanently set to 10 Hz and the detector signal 8 is measured. A frame with three particulars is respectively shown in the illustrations of Figures 3-6 to the left next to each signal curve. The first two particulars therein denote the scaling on the axes of the storage oscilloscope. The first values states how many milliseconds between two markings in a box on the abscissa, on which the time is entered, denote [sic]. The second value states how many volts on the ordinate, on which the voltage is entered, the distance between two markings or, respectively, in a box amounts to. The third value represents the actual result, namely a specific voltage that, counted in volts or millivolts, can be converted, for example for an amplitude signal or a phase signal.

Measured values for reference, phase and detector signal given a 10 Hz modulation of both choppers 1, 2 are respectively shown on Figures 3 and 4. The same presentations as in Figures 3 and 4 are employed in Figures 5 and 6, whereby, however, the modulation of the first chopper 1 amounts to 40 Hz and that of the second chopper 2 amounts to 20 Hz.

The basis of the illustrated measured values and results according to Figure 4 contain [sic] that both choppers are permanently set to 10 Hz, and that the detector signal 8 is measured. The uppermost curve at the right represents the curve

of the pulse sequence at the chopper 1. A complete oscillation thereby requires the length of two boxes or, respectively, twice 50 ms, so that a frequency of 10 Hz is present here. The same is true of the middle curve, which is present at the second chopper 2. The lowest curve represents the detector signal 8, which is an analog signal at first. In all three instances, the amplitude of the signal is respectively entered as third value in the juxtaposed frame, whereby this [sic], however, are selectable trial parameters.

Figure 2 shows both the reference as well as the phase given a modulation of 10 Hz for both choppers 1, 2. The pulse frequency is identical to the frequency in Figure 3. The phase position of the choppers 1, 2 is nearly identical to -584 mV and -591 mV which, when converted, approximately corresponds to a phase shift of 60°. What thereby forms the basis is that 10 mV stands for 1° phase shift. Expressed in other words, the infrared wave or, respectively, heat wave reflected back from the specimen 7 has a phase position that lags behind the phase of the laser signal by 60°.

Figure 5 and 6 show signals corresponding to Figures 3 and 4. This time, however, the first and second chopper 1, 2 are modulated on different frequencies. The first chopper 1 respectively comprises a pulse frequency of 40 Hz, and the second chopper 2 comprises a pulse frequency of 20 Hz. The detector signal 8 is again a result signal superimposed of a plurality of signals that is converted via the signal processing applied in the method. Corresponding to the second and fourth signal in Figure 6, the phase position for the two drive frequencies is also approximately the same for the case illustrated in Figures 5 and 6.

It can thus be documented by the measurements that it is possible to also correctly obtain the phase when the specimen is simultaneously modulated with two different frequencies instead of tuning the modulation frequency (chirp) as hitherto.

The measurement with the described mechanical choppers represents only one embodiment, whereby the modulation of laser diodes or, respectively, of LEDs with a plurality of frequencies simultaneously is planned. Over and above this, the planar illumination of the specimen 8 can be optimized with appropriate devices, as can the image registration with a camera arrangement. The basis thereby continues to be formed by the principle that the measuring time is shortened by simultaneous

multi-frequency excitation and by simultaneous parallel evaluation of the different frequencies.

When it is required to simultaneously determine the geometrical and thermal parameters of a multi-layer structure, then this may not be possible with traditional calculating methods. An analytical formula for the phase dependent on the thermal and geometrical parameters as well as on the modulation frequency can be specified. When, however, this is to be solved for the quantities characterizing the multi-layer structure, then this is not possible analytically. This means that there is an "inverse problem". The interpretation can then ensue on the basis of numerical methods such as, for example, regression analysis or with a neural network, which represents and automation of the determination of the material parameters and involves a higher precision and a time-savings. Moreover, the possibility is opened up of theoretically describing arbitrary layer structures to be photothermally measured and of determining their thermal and geometrical properties.

Patent Claims

1. Thermal wave measuring method for contact-free measurement of geometrical and/or thermal features of a layer structure, whereby a modulatable heat source is driven with different frequencies and the layer structure is periodically heated, infrared radiation emitted by the layer structure and correspondingly modulated in intensity is received and is respectively evaluated as function of a drive frequency on the basis of amplitude and/or phase, whereby the heat source is simultaneously amplitude-modulated with at least two, predetermined, discrete frequencies, and the infrared radiation emitted by the layer structure is simultaneously interpreted corresponding to the drive frequencies.

2. Method according to claim 1, wherein a laser or, respectively, a laser diode or a light-emitting diode (LED) is employed as heat source.

3. Method according to one of the preceding claims, wherein the discrete frequency parts of the drive frequencies are adapted to a measurement problem.

4. Method according to claim 1 or 2, wherein the predetermined frequencies are detected with a lock-in evaluation.

5. Method according to claim 1, 2 or 3, wherein a fast Fourier transformation (FFT) is provided for the evaluation of the individual frequencies.

6. Method according to claim 4 or 5, wherein a farther-reaching evaluation occurs on the basis of a regression analysis or with a neural network.

7. Method according to one of the preceding claims, wherein the method is calibrated to a specific layer structure with calibration both my means of mathematically specific, theoretical values as well as by experimentally supported data.

8. Method according to one of the preceding claims for determining geometrical features given known thermal features or thermal features given known geometrical features of the layer structure.

Abstract

Thermal Wave Measuring Method

The simultaneous multi-frequency excitation with two or more discrete frequencies of an electrically modulatable hot light source enables the parallel evaluation corresponding to the different drive frequencies. As a result thereof, the measuring time in the measurement of multi-layer systems is significantly shortened. As a result of a suitable selection of the discrete frequency parts of the drive frequencies, these can be adapted to the measurement problem.

Figure 1

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FIG 1

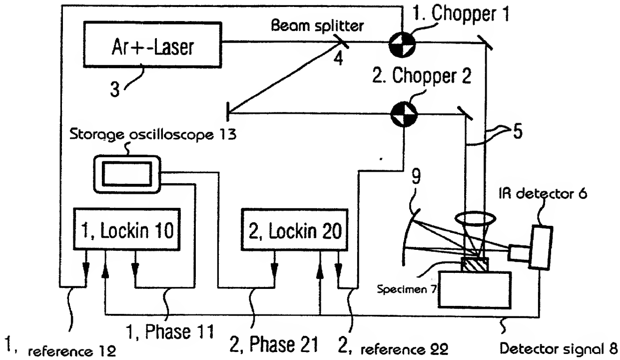


FIG 2

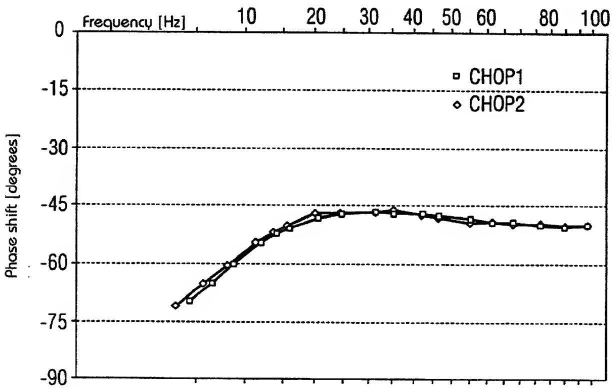


FIG 3

Reference and Detector Signal Given a Modulation of 10 Hz for Both Choppers

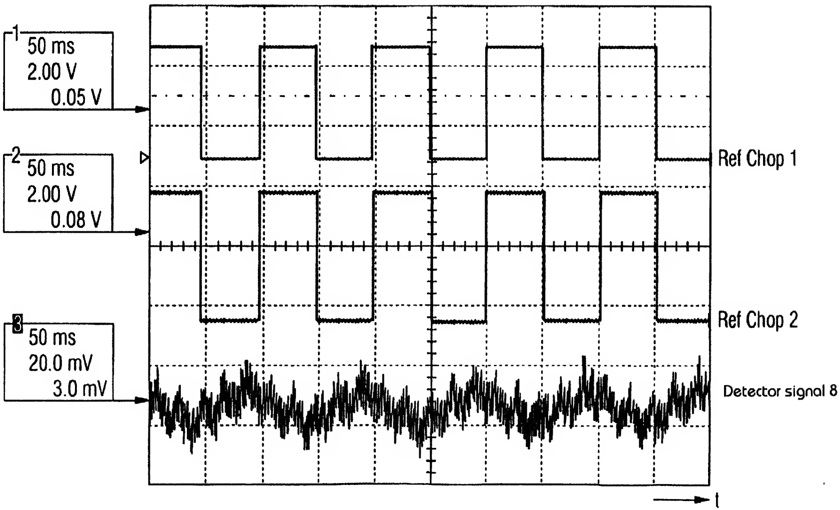


FIG 4

Reference and Phase Given a Modulation of 10 Hz for Both Choppers

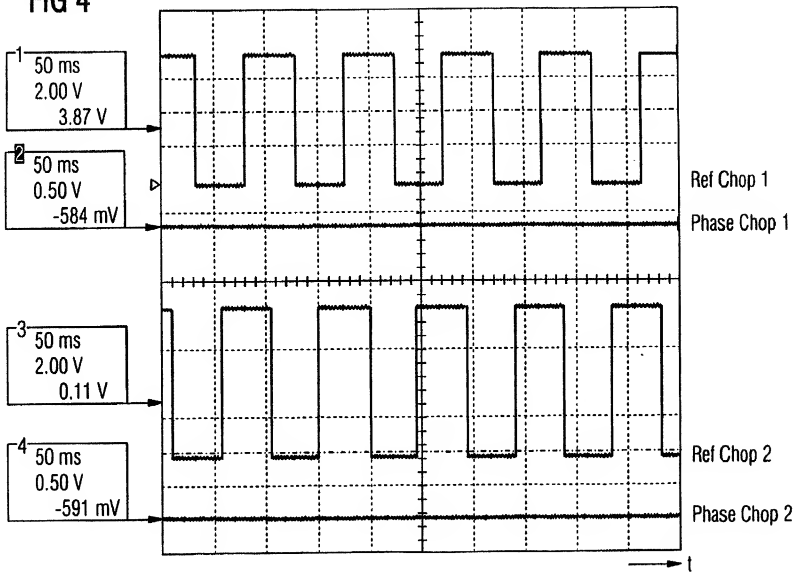


FIG 5

Reference and Detector Signal Given a Modulation of 40 Hz and 20 Hz

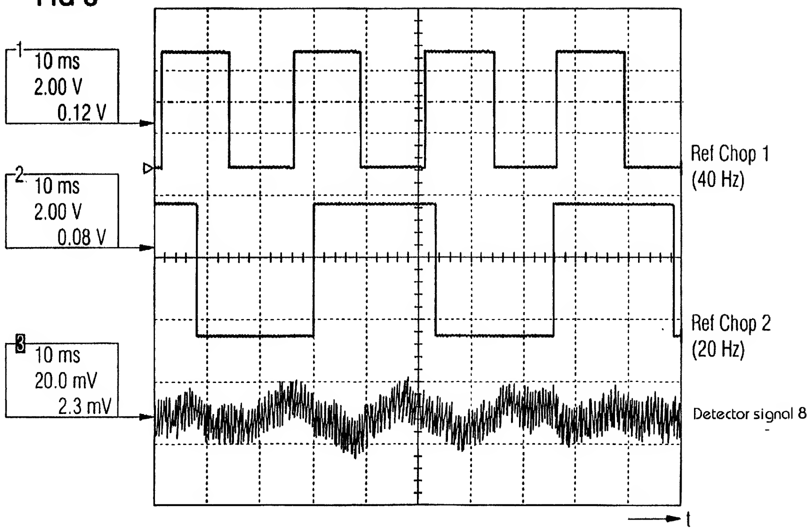
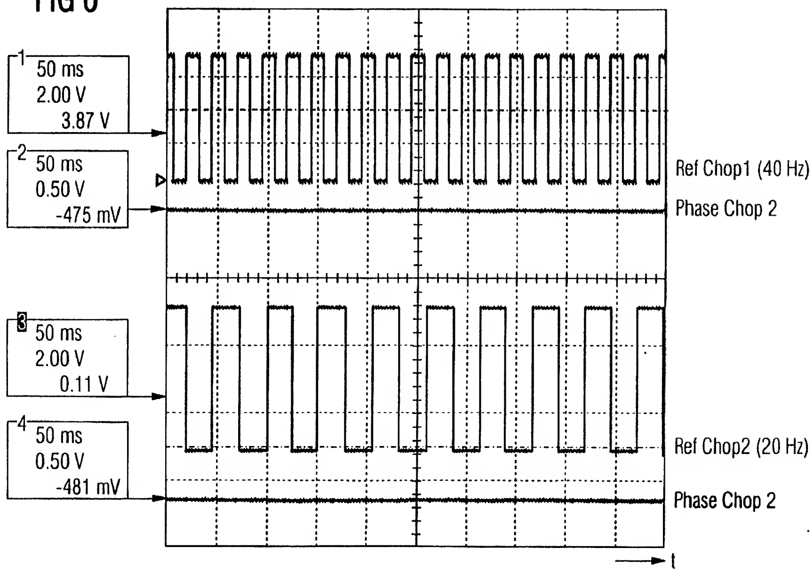


FIG 6

Reference and Phase Given a Modulation of 40 and 20 Hz



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APPLICANT(S):	JOACHIM BAUMANN ET AL.
ATTORNEY DOCKET NO.:	P01,0008
INTERNATIONAL APPLICATION NO:	PCT/DE99/02590
INTERNATIONAL FILING DATE:	18 AUGUST 1999

INVENTION: THERMAL WAVE MEASURING METHOD

Assistant Commissioner for Patents,
Washington D.C. 20231

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Members of the firm of Hill & Simpson designated on the original Power of Attorney have merged into the firm of Schiff Hardin & Waite. All future correspondence for the above-referenced application therefore should be sent to the following address:

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Washington D.C. 20231

APPOINTMENT OF ASSOCIATE POWER OF ATTORNEY

Dear Sir:

I am an attorney designated on the Power of Attorney for the above-referenced application. I hereby appoint Mark Bergner (Reg. No. 45,877) as an associate attorney, with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith.

Submitted by,

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Declaration and Power of Attorney For Patent Application
Erklärung Für Patentanmeldungen Mit Vollmacht
German Language Declaration

Als nachstehend benannter Erfinder erkläre ich hiermit an Eides Statt:

As a below named inventor, I hereby declare that:

dass mein Wohnsitz, meine Postanschrift, und meine Staatsangehörigkeit den im Nachstehenden nach meinem Namen aufgeführten Angaben entsprechen,

My residence, post office address and citizenship are as stated below next to my name,

dass ich, nach bestem Wissen der ursprüngliche, erste und alleinige Erfinder (falls nachstehend nur ein Name angegeben ist) oder ein ursprünglicher, erster und Miterfinder (falls nachstehend mehrere Namen aufgeführt sind) des Gegenstandes bin, für den dieser Antrag gestellt wird und für den ein Patent beantragt wird für die Erfindung mit dem Titel:

Thermowelen-Messverahren

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

deren Beschreibung

(zutreffendjhaes ankreuzen)

☒ hier beigefügt ist.

☐ am ____________ als
PCT internationale Anmeldung
PCT Anmeldungsnummer ____________
Eingereicht wurde und am ____________
Abgeändert wurde (falls tatsächlich abgeändert).

the specification of which

(check one)

☐ is attached hereto.

☐ was filed on ____________ as
PCT international application
PCT Application No. ____________
and was amended on ____________
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Ich bestätige hiermit, dass ich den Inhalt der obigen Patentanmeldung einschliesslich der Ansprüche durchgesehen und verstanden habe, die eventuell durch einen Zusatzantrag wie oben erwähnt abgeändert wurde.

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims as amended by any amendment referred to above.

Ich erkenne meine Pflicht zur Offenbarung irgendwelcher Informationen, die für die Prüfung der vorliegenden Anmeldung in Einklang mit Absatz 37, Bundesgesetzbuch, Paragraph 1.56(a) von Wichtigkeit sind, an.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, §1.56(a).

Ich beanspruche hiermit ausländische Prioritätsvorteile gemäss Abschnitt 35 der Zivilprozessordnung der Vereinigten Staaten, Paragraph 119 aller unten angegebenen Auslandsanmeldungen für ein Patent oder eine Erfindersurkunde, und habe auch alle Auslandsanmeldungen für ein Patent oder eine Erfindersurkunde nachstehend gekennzeichnet, die ein Anmeldedatum haben, das vor dem Anmeldedatum der Anmeldung liegt, für die Priorität beansprucht wird.

I hereby claim foreign priority benefits under Title 35, United States Code, §119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

German Language Declaration

Prior foreign appplications
Priorität beansprucht

Priority Claimed

(Number) (Nummer)	(Country) (Land)	(Day Month Year Filed) (Tag Monat Jahr eingereicht)	Yes Ja	No Nein
198 37 889.0	Germany	20.. August 1998	☒	☐
			☐	☐
			☐	☐

Ich beanspruche hiermit gemäss Absatz 35 der Zivilprozessordnung der Vereinigten Staaten, Paragraph 120, den Vorzug aller unten aufgeführten Anmeldungen und falls der Gegenstand aus jedem Anspruch dieser Anmeldung nicht in einer früheren amerikanischen Patentanmeldung laut dem ersten Paragraphen des Absatzes 35 der Zivilprozeßordnung der Vereinigten Staaten, Paragraph 122 offenbart ist, erkenne ich gemäss Absatz 37, Bundesgesetzbuch, Paragraph 1.56(a) meine Pflicht zur Offenbarung von Informationen an, die zwischen dem Anmeldedatum der früheren Anmeldung und dem nationalen oder PCT internationalen Anmeldedatum dieser Anmeldung bekannt geworden sind.

I hereby claim the benefit under Title 35. United States Code. §120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, §122, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, §1.56(a) which occured between the filing date of the prior application and the national or PCT international filing date of this application.

(Application Serial No.) (Anmeldeseriennummer)	(Filing Date) (Anmeldedatum)	(Status) (patentiert, anhängig, aufgegeben)	(Status) (patented, pending, abandoned)
(Application Serial No.) (Anmeldeseriennummer)	(Filing Date) (Anmeldedatum)	(Status) (patentiert, anhängig, aufgeben)	(Status) (patented, pending, abandoned)

Ich erkläre hiermit, dass alle von mir in der vorliegenden Erklärung gemachten Angaben nach meinem besten Wissen und Gewissen der vollen Wahrheit entsprechen, und dass ich diese eidesstattliche Erklärung in Kenntnis dessen abgebe, dass wissentlich und vorsätzlich falsche Angaben gemäss Paragraph 1001, Absatz 18 der Zivilprozessordnung der Vereinigten Staaten von Amerika mit Geldstrafe belegt und/oder Gefängnis bestraft werden koennen, und dass derartig wissentlich und vorsätzlich falsche Angaben die Gültigkeit der vorliegenden Patentanmeldung oder eines darauf erteilten Patentes gefährden können.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

German Language Declaration

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And I hereby appoint

19

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Unterschrift des Erfinders: Th. Mangold — Datum: 6/10/99	Second Inventor's signature — Date
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D-81547 München Bundesrepublik Deutschland	

(Bitte entsprechende Informationen und Unterschriften im Falle von dritten und weiteren Miterfindern angeben).	*(Supply similar information and signature for third and subsequent joint inventors).*